A MODIFIED TECHNIQUE FOR SIMULATION OF GREAT EARTHQUAKE: A CASE STUDY OF SUMATRA EARTHQUAKE

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ABSTRACT

The present study is aimed to model the strong motion data due to 26th December, 2004 earthquake at various sites from a rupture model which can be used for further studies related to seismic hazards. Strong motion data provide basic information for designing earthquake resistant parameters required for safe engineering structure. It also provides information to study various property of the source of an earthquake. Strong ground motion simulation techniques helps in obtaining data in a region uncovered by strong motion instrumentation. This work presents modified semi-empirical green's function technique for simulation of strong ground motion due to the rupture source of great earthquake. The coastal region of Sumatra Island has been visited by a great earthquake on 26th December, 2004. The earthquake is known for release of high amount of energy and the devastating Tsunami. This earthquake has been recorded at several broadband stations including a nearest broadband station in Indonesia. In this work records has been simulated using modified semi-empirical technique initially proposed by Midorikawa [1993] and later modified by Joshi and Midorikawa [2004]. Modifications in this technique have been made to remove dependency of the technique on attenuation relation. The rupture model for this earthquake has been tested for various location of nucleation point and rupture velocity. Iterative modeling and comparison suggest that the rupture initiated at the northern corner of rupture at a depth of 38 km and started propagating in all direction with rupture velocity 2.0 km/sec. The distribution of peak ground acceleration in the near source region has been computed from simulated record at several locations. The records from final model has been simulated and compared at MDRS and VISK stations in the coastal region of India. The comparison confirms the efficacy of the approach and the suitability of final model for predicting strong ground motion.

INTRODUCTION

Strong motion studies play important roles in both earthquake engineering and seismology. It provides the information for designing earthquake resistant parameters required for safe engineering structure and study of various source parameters of an earthquake. There are several techniques which can be used to simulate strong ground motion due to finite rupture source buried in a defined velocity medium. The method of modified semi-empirical simulation of strong ground motion has been evolved as an effective tool for prediction of strong motion parameters. This method has advantage of both empirical green's function technique [Hartzell, 1978], [Kanamori, 1979], [Hadley and Helmberger, 1980], [Irikura, 1983], [Houston and Kanamori, 1984] and [Heaton and Hartzell, 1986] and stochastic simulation technique [Hanks and McGuire, 1981], [Boore, 1983], [Boore and Joyner, 1991]. The method of semi empirical modeling has been given by Midorikawa [1993] and modified by Joshi and Midorikawa [2004]. In this technique synthetic records from different subfaults within the rupture plane are used in place of aftershock records as green's function. The advantage of the proposed semi-empirical technique is that it is very fast to calculate and is based on simple attenuation relations and modeling parameters which are easy to predict. However dependency of semi-empirical method on attenuation relation itself poses a constraint on its applicability, especially for the case of modeling great earthquake using empirically generated attenuation relations. The semi-empirical method of simulation has been used for strong motion simulation of major to large earthquake in a broad frequency range [Joshi, 2004], [Joshi and Midorikawa, 2004], but the method has never been used for simulating records due to great earthquakes. In order to include the faulting mechanism associated with the great earthquake, modifications in the semi-empirical method has been made to incorporate the effect of radiation pattern and seismic moment.

Recently a great earthquake (M_w 9.0) which occurred on 26th December, 2004 in the Sumatra region has devastated entire south Asia. This earthquake has raised concern over the safety of structures in the coastal region of various south Asian countries including India. This earthquake is recorded on several broadband stations worldwide.

In order to understand high frequency nature of strong ground motion produced during this great earthquake, strong motion record have been simulated. The simulation technique used for model such great earthquake needs to be effective in synthesizing the acceleration record for comparing the simulated records with observed broadband data. Due to complexities of slip mechanism of this mega-thrust earthquake and dependency of other simulation methods on slip distribution, we have used the modified semi-empirical technique for simulation of strong motion data of this earthquake. In the present work modifications in semi-empirical technique has been made to remove its dependency on attenuation relation which has many constraints. The present study is aimed to model the strong motion data due to the great Sumatra earthquake at various sites from a rupture model which can be used for further studies related to seismic hazards.

METHODOLOGY OF SIMULATION

It is seen that the Empirical Green's Function (EGF) technique is the most reliable technique of strong motion simulation but it has limited applicability due to its major requirement of aftershock or foreshock of target event to be modeled. In an attempt to remove dependency of EGF technique on aftershocks, Midorikawa [1993] has proposed a semi-empirical green's function approach where the aftershocks are replaced by empirically generated green's function. The theoretical development has been made in such a way that this method satisfies the property of omega square source model. The modified semi-empirical method proposed by Joshi and Midorikawa [2004] uses the concept of stochastic simulation technique together with semi-empirical technique for complete simulation of strong motion time series. In the first part of this technique a time series having basic spectral shape of accelerogram is simulated while in the second part deterministic model of rupture source has been used to simulate the accelerogram. The modified semi-empirical method uses the time series obtained from stochastic simulation and envelope obtained using semi empirical approach. In the stochastic simulation technique the white Gaussian noise has been passed through number of filters representing the earthquake processes. The shapes of these filters are defined by Boore [1983]. Following is the functional form of the observed acceleration spectra at particular station at distance R:

$$A(f) = CS(f)P(f)F(f,R) \tag{2.1}$$

Where, C is a constant scaling factor which include radiation pattern coefficient for SH wave is used in this work, filter *S(f)*is the source spectrum, filter *P(f)* is the near-site attenuation of high frequencies and filter *F(f,R)* is the effect of anelastic attenuation. The radiation pattern is dependent on type of faulting mechanism and the geometry of earthquake source. The white noise after passing through filters in eq. (2.1) gives basic spectral shape which represents the acceleration spectra. This requires proper windowing of spectra through a function which represents deterministic model of rupture process. Such deterministic time window has been proposed by Midorikawa [1993] which computes envelope of accelerogram from a model of rupture plane divided into several subfaults. The division of subfaults is based on self similarity law proposed by Kanamori and Anderson [1975]. The acceleration envelope waveform is determined from the relation modified by Joshi [2004] after Kameda and Sugito [1978]. The transmission factor contributes significantly to shaping the attenuation rate of the peak ground acceleration with respect to the distance from the source. This means that we should take this factor into consideration when modeling an intermediate to deep focus earthquake. The duration parameter 'T_d' used in acceleration envelope waveform relation has been calculated using following relation derived by Midorikawa [1989]:

$$T_d = 0.0015\text{x } 10^{0.5M} + 0\ .12\ R^{0.75} \tag{2.2}$$

A small modification in this relation was necessary in order to fit this relation with the actual data of the great Sumatra earthquake of 26th Dec, 2004. The new modified form of eq. (2.2) is given as follows:

$$T_d = 0.0015\text{x } 10^{0.5M} + 0.2\ R^{0.81} \tag{2.3}$$

The parameters required to define the model of the rupture plane are its length, width, length and width of the elements (L_e, W_e) within the rupture plane, nucleation point, strike and dip of rupture plane (φ, δ), rupture velocity (V_r) and shear wave velocity in the medium. To simulate the ground motion at the observation point, the rectangular rupture plane causing a target earthquake is divided into several elements that represent smaller earthquakes. The total numbers of elements within the rupture plane are N^2, which determines the magnitude of the elementary earthquakes is based on the earthquake source scaling relation of Kanamori and Anderson [1975]. A correction function F(t) is convolved with the obtained acceleration records for each subfaults to adjust the difference in the slip-time function between the small and the large event. The energy released is recorded in the form of acceleration record $ac_{ij}(t)$. The summation of all records reaching the observation point at different time lag gives the resultant record 'Ac(t)', expressed by the following equation:

$$Ac(t) = \sum_{i=1}^{M} \sum_{j=1}^{N} ac_{ij}(t-t_{ij})$$

In this expression M and N are the total number of elements along the length and the width of the rupture plane, respectively. The parameter t_{ij} is used to represent time taken by the rupture to reach the observation point from each element. The arrival time of the accelerogram from subfault at the observation point depends on the geometry of the rupture plane, the model of the earth, the rupture propagation and the location of the observation point. Depending on the travel time; the transmission coefficient and the radiation pattern, accelerogram released by different elements arrive at the observation point at different time lags. Summation of all of these accelerogram gives the accelerogram at the observation point.

SIMULATION FOR 2004 NIIGATA EARTHQUAKE

On the 23rd of October 2004 at 17:56 (JST), an earthquake (M_{JMA} 6.8) struck Mid Niigata prefecture, at 80 km south of Niigata city, on the west coast of Honshu, Japan [Bardet, 2004]. For the purpose of simulation, acceleration data are used at three stations (NIG019, NIG028, and NIG016) of K-NET of the NIED. The locations of rupture responsible for this earthquake is basically determined referring by Honda et al. [2005] and used Q(f) relation is an average relation for Japan and has been already tested by Joshi and Midorikawa [2004] for simulation of strong ground motion of the Geiyo earthquake of 2001, Japan. The rupture plane is divided into 24 subfaults, and it is assumed that rupture starts from (4, 3) nucleation point. From Fig. 1 it is seen that observed and simulated records are closely matched in terms of peak ground acceleration, and their pseudo velocity response spectra are matched for high and low frequencies. This confirms the applicability of the modified semi-empirical technique for this earthquake.

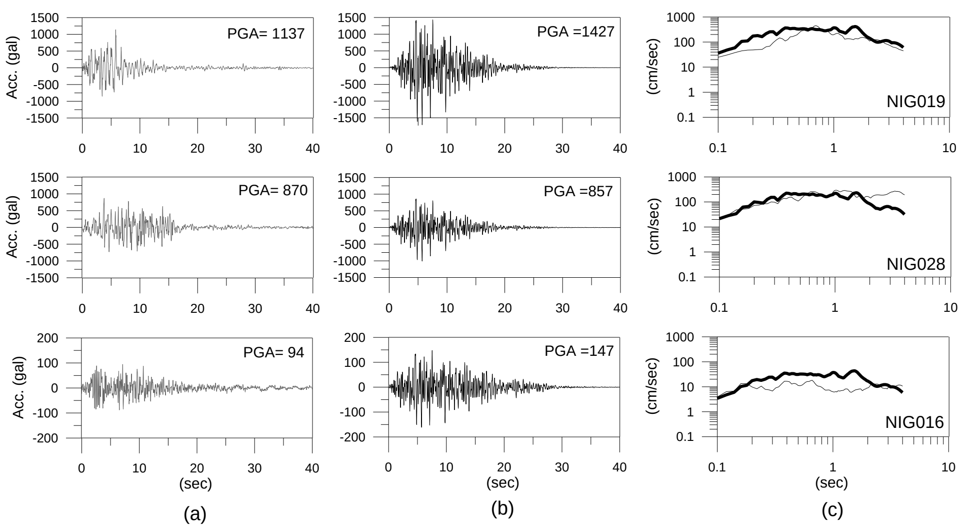


Fig. 1: (a) Observed, (b) Simulated acceleration record and (c) Comparison of pseudo velocity response spectra prepared from NS components of observed and simulated records at NIG019, NIG028 and NIG016 stations. The station names are shown inside the figure showing response spectra. The response spectra shown by thin line represent that prepared from observed record

METHODOLOGY: DISCUSSION

One of the most important characteristics of the strong motion data is its dependency on directivity effects. The approach of semi-empirical modeling clearly follows directivity effects [Midorikawa, 1993]. In the present work seismic moment has been used for scaling the amplitude of accelerogram together with the radiation pattern. These modifications require an investigation of the property of directivity. In order to check the effect of directivity in the technique, strong motion records are simulated on both sides of the rupture plane for bilateral and unilateral rupture propagations. For simplicity in approach vertical rupture plane of length 750 km and downward extension 150 km has been assumed. The rake of this rupture is assumed to be similar with that of the Sumatra earthquake which gives a pure thrust mechanism. Variation of peak ground acceleration on both sides of the rupture plane in a strike direction for unilateral rupture propagation and bilateral rupture propagation is shown in Fig. 2. Fig. 2 shows in the case of unilateral rupture propagation, peak ground acceleration values are higher in the direction of rupture propagation compared to peak ground accelerations in the opposite direction of rupture propagation. For bilateral rupture propagation, symmetry is observed in the attenuation curves obtained on both side of the rupture plane. This confirms the presence of directivity effect in the modified technique present in this paper.

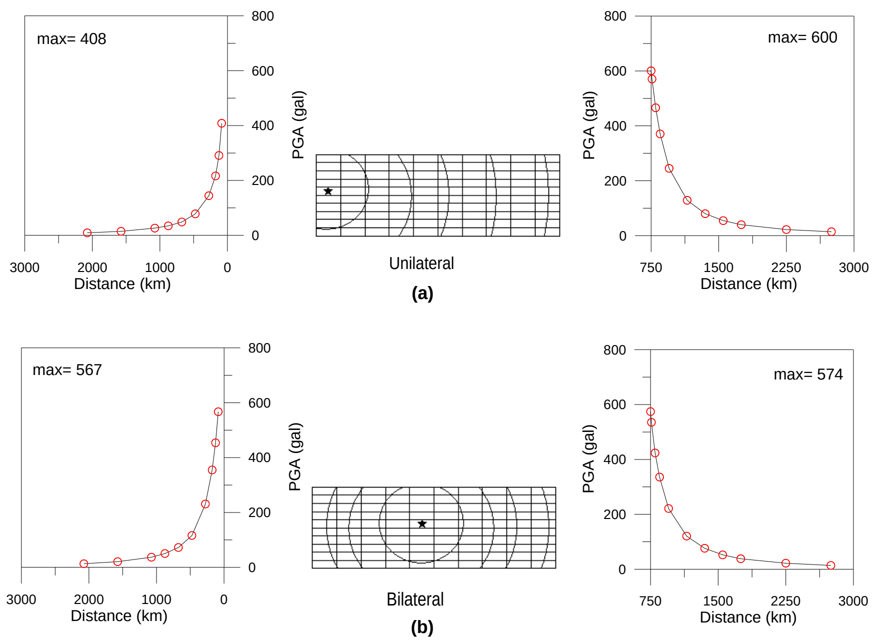


Fig. 2: Attenuation curve for the case of (a) unilateral and (b) bilateral rupture propagation

SUMATRA EARTHQUAKE: GENERATION OF SYNTHETIC GROUND MOTION

The present study is aimed to use semi-empirical method to provide estimate of rupture velocity and rupture propagation of Sumatra earthquake by simulating its record at various observation points. The parameters of Sumatra earthquake is given in Table 1. The Sumatra earthquake of 26th December, 2004 of magnitude 9.0 (M_w) occurred at 00:58:53s GMT was recorded at 14 stations of OHP (Ocean Hemisphere network Project), Japan. Among these the closest broadband station is PSI at an epicentral distance of 355 km in Indonesia. The sensor at PSI station has sensitivity 0.75×10^8 count/m/s with sampling frequency 20 samples per sec. The record at PSI station is obtained in seed format. The collected records have been processed after proper conversion into readable format. For correctly representing particle ground motion at the station the record at PSI station has been bandpassed in a frequency range 0.3 to 4.0 Hz.

Table 1: Parameters of the Sumatra, Indonesia earthquake of 26th December, 2004

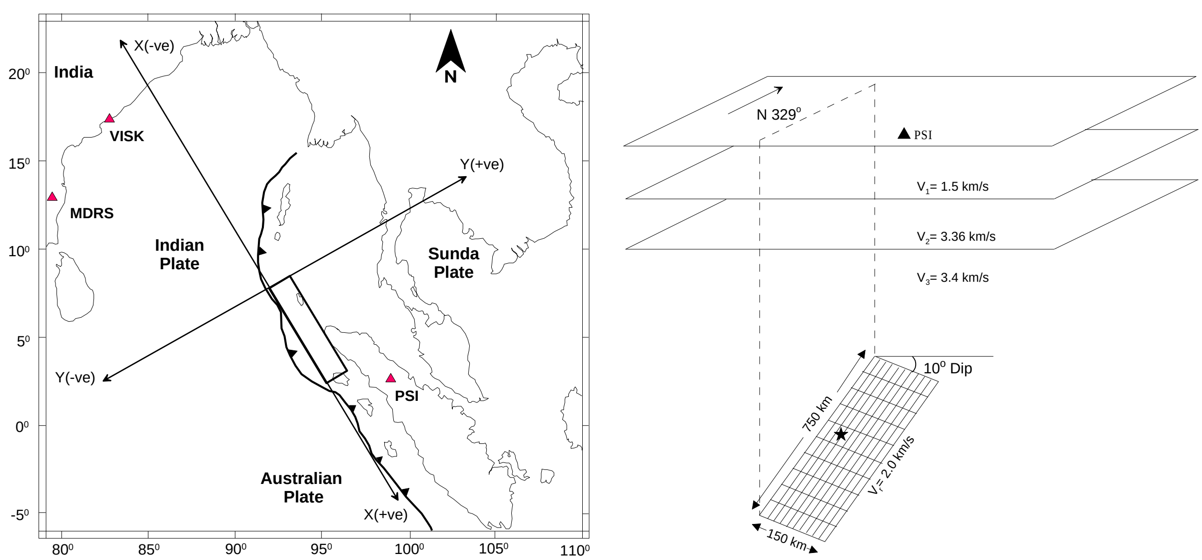
Hypocenter	Size	Fault plane solution	Reference
3.09° N 94.26° E 29 Km	$M_0 = 4.0\times10^{22}$ Nm M_w=9.0	φ= 329° δ= 8° λ= 110°	CMT HARVARD
3.29° N 95.77° E 30 Km	$M_0 = 2.5\times10^{22}$ Nm M_w =8.2	φ= 274° δ= 13° λ= 55°	USGS
3.09° N 94.26° E 29 Km	$M_0 = 6.5\times10^{22}$ Nm M_w =9.1	φ= 340° δ= 14° λ= 110°	Lay et al., [2005]

Strong motion modeling of a rupture plane using semi empirical approach require various parameters like length, width, nucleation point, velocity structure, rupture velocity, location and geometry of rupture plane and its subfaults. The geometrical parameters of subfaults can be calculated using the self similarity laws given by Kanamori and Anderson [1975]. In the present work the geometry and location of the rupture responsible for Sumatra earthquake is kept similar to that used by Sorensen et al. [2007] and are given in Table 2. The entire rupture plane of area 750 x 150 sq km is divided into 100 subfaults. Each subfault represents an earthquake of magnitude 7.0 (M_w). The rupture model of Sumatra earthquake is placed in a velocity structure given by Sorensen et al. [2007] is shown in Fig. 3.

Table 2: Parameters of the rupture model of the Sumatra earthquake

Modeling Parameter	Source
Length = 750 km	Lay et al., [2005]
Width = 150 km	Yagi, [2004]
Dip = 10°	Yagi, [2004]
Strike = 329°	CMT HARVARD
Rake = 110°	CMT HARVARD
N_L = 10, N_W = 10	Based on scaling relation by Kanamori and Anderson, [1975]
V_r = 2.0 km/sec	Alessio and Stefano, [2007]
Q(f) = $100f^{0.8}$	Sorensen et al., [2007]

Software named MSEMP (Modified Semi Empirical Modeling Program) in FORTRAN has been prepared to simulate records at any observation point using modified technique. This software require coordinates of recording station and rupture plane in a Cartesian system where X and Y axes are parallel to strike and dip direction of the rupture plane, respectively. In order to select the nucleation point records have been simulated at PSI station for its several possibilities. In order to compare the simulated record with the observed velocity record the simulated acceleration record is integrated using property of Fourier transform. This simulated velocity record is filtered with the same band pass filter as used for the processing of observed velocity record at PSI station. The selected range removes low frequencies from the record which are difficult to simulate. Various simulated records and its comparison with observed record for different possibilities of nucleation point are shown in Fig 4. The simulated and observed waveforms due to S wave at PSI station are compared in terms of root mean square error. It is seen that nucleation point (5, 3) indicated by rectangle 4 at depth of 38 km gives minimum error and has been retained for further use.



(a) (b)

Fig. 3: (a) Location of rupture responsible for the Sumatra earthquake in a cartesian system where X and Y axes are parallel to strike and dip direction of the rupture plane (in rectangle), respectively. Location of stations at which simulation is made is shown by solid red triangles. (b) Rupture model of the Sumatra earthquake consisting of 10×10 subfaults. Solid triangle shows the location of PSI station and star shows the starting position of rupture

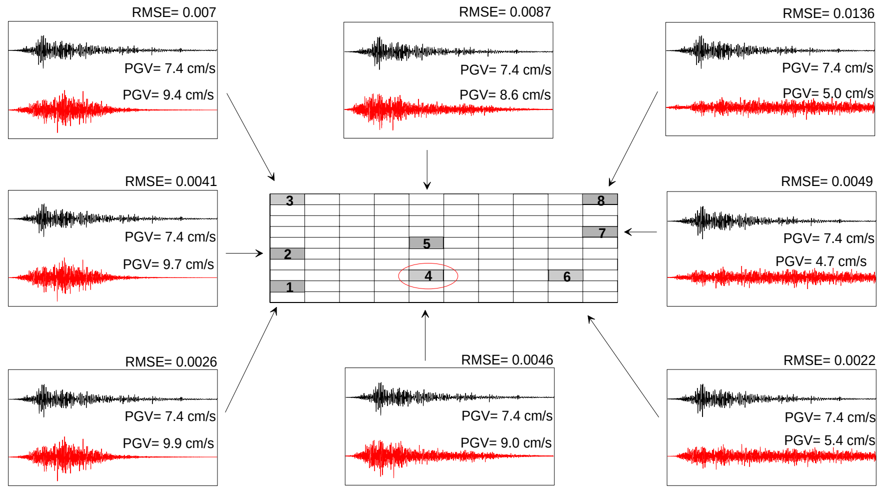


Fig. 4: Filtered observed and simulated record at PSI station is shown in boxes for different nucleation points. Nucleation points are shown by arrows and simulated record is shown by red color. Filter range for both observed and simulated record is between 0.3 to 4.0 Hz. Root mean square error for each simulation is shown in each box

In all of the models used for selecting nucleation point rupture velocity has been assumed as 2.0 km/sec [Alessio and Stefano, 2007]. Simulated acceleration record at PSI station is shown in Fig. 5a. The comparison between actual and simulated velocity record at PSI station is shown in Fig. 5. Comparison shows that simulated record bears realistic shape as that of observed record and the peak ground velocity of observed and simulated record is also comparable. This confirms the suitability of the model and its selected parameters.

In this work we have simulated records at PSI, MDRS and VISK stations which are in the coastal regions of Indian subcontinent. Locations of these stations in the assumed coordinate system are shown in Fig. 3. The simulations at VISK and MDRS stations of IMD (India Meteorological Department) which are at epicentral distance of 2100 km and 2060 km respectively are shown in Fig. 6. The comparison of simulated record properly bandpassed through filters used for processing of observed record shows that the method is capable of effectively simulating peak ground velocities at these stations. A comparison of spectral contents of velocity records at these three stations is shown in Fig. 7. The comparison shows the capability of method to properly simulate frequency contents actually present in the observed records. A comparison of parameters of simulated and observed records in Table 3 confirm the efficacy of modified semi empirical approach to model a great earthquake.

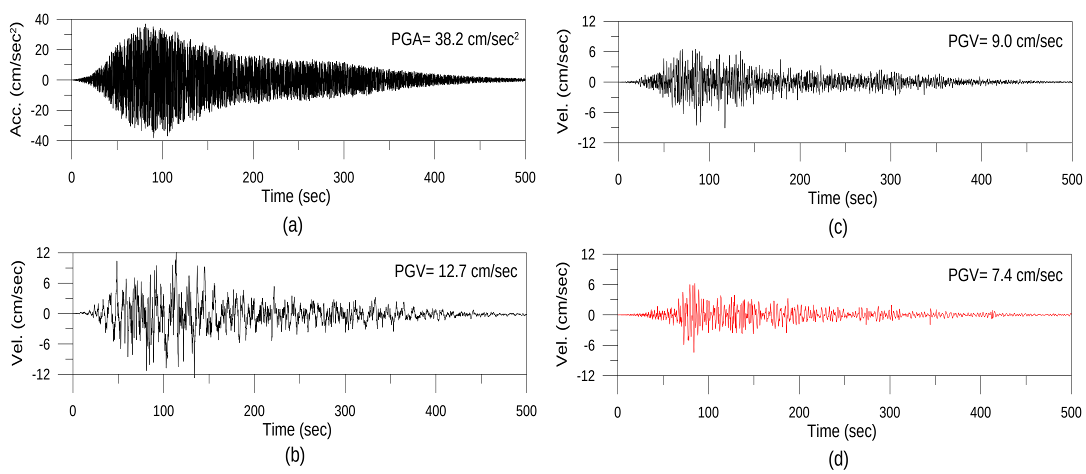


Fig. 5: (a) Simulated accelerogram at PSI station, (b) velocity record obtained from integration of simulated acceleration record, (c) Filtered velocity record in a range of 0.3 to 4.0 Hz and (d) Observed velocity record at PSI station filtered in a range of 0.3 to 4.0 Hz and (e) Comparison of simulated and observed record at PSI station. The red lines in figure shows observed velocity record filtered in a range of 0.3 Hz to 4.0 Hz

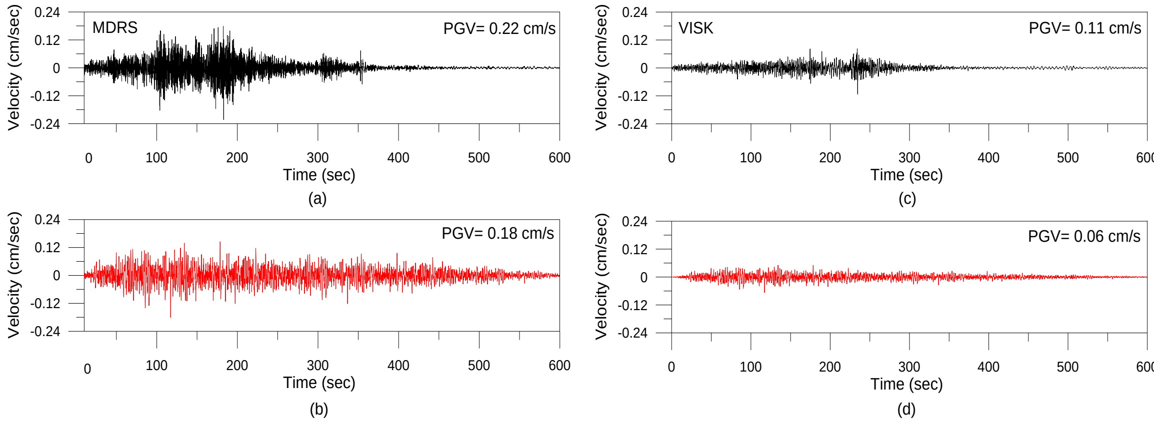


Fig. 6: Filtered (a) observed and (b) simulated velocity record at MDRS station, (c) observed and (d) simulated velocity record at VISK station

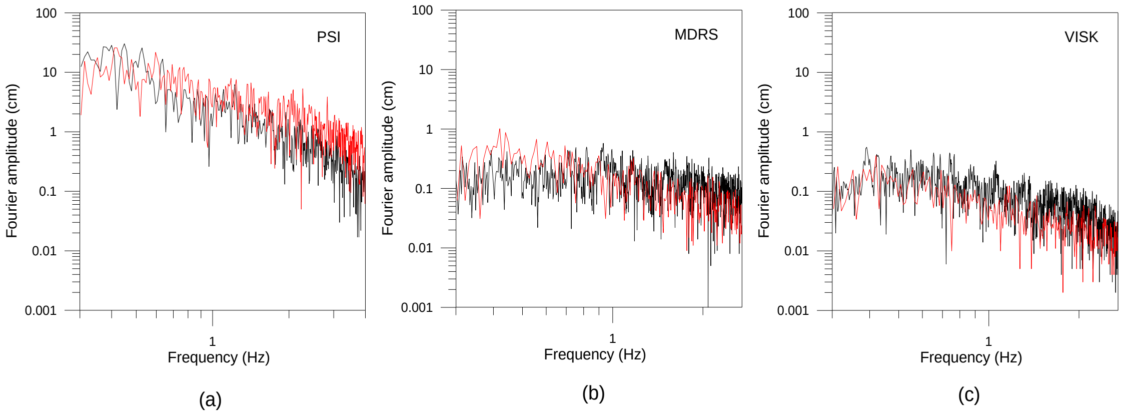


Fig. 7: Comparison of observed (black) and simulated (red) amplitude spectra of velocity record at (a) PSI, (b) MDRS and (c) VISK stations. The observed and simulated records are filtered between 0.3 to 4.0 Hz at PSI station, while at MDRS and VISK station records are filtered between 0.3 to 2.5 Hz

Table 3: Parameters of the simulated and observed records at various stations

Stations	Observed PGV (cm/sec)	Simulated PGV (cm/sec)	Observed Predominant Frequency (Hz)	Simulated Predominant Frequency (Hz)
PSI	7.4	9.0	0.44	0.42
MDRS	0.22	0.18	0.93	0.42
VISK	0.11	0.06	0.39	0.42

In an attempt to model hypothetical great earthquake close to the territory of Indian subcontinent, the northern segment of Andaman ridge shown in Fig. 8 has been selected as location of probable causative fault. The strike of the hypothetical rupture at this segment is assumed as 6º N. The modeling parameters of rupture are assumed to be same as that of the Sumatra earthquake. The velocity structure is assumed as that given by Parvez et al. [2003] for Andaman region and the depth of rupture plane is assumed at 17 km. Using assumed model the simulated acceleration records and its pseudo acceleration response spectra at MDRS, VISK and PB stations is shown in Fig. 8. The acceleration record at PB station shows that the peak ground acceleration of order 2663 gal can be obtained. The order of peak ground acceleration obtained for this earthquake shows the seismic hazard potential of any probable great earthquake is very high in this region.

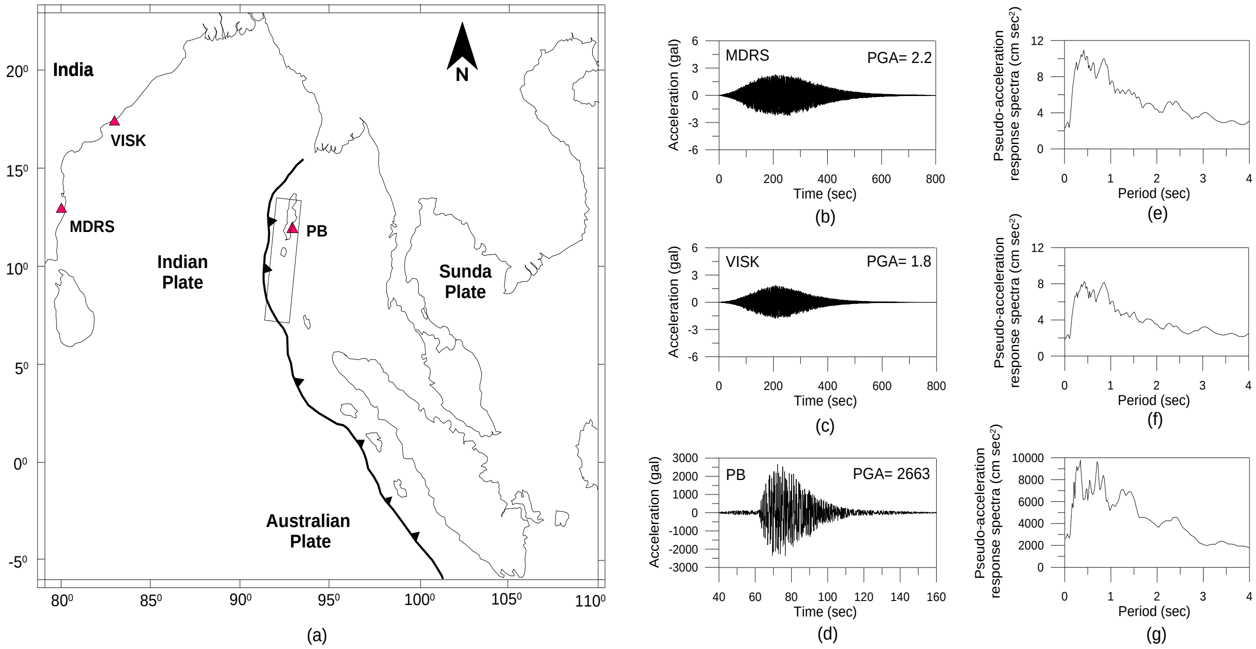


Fig. 8: (a) Location of rupture for hypothetical earthquake in Andaman region shown by rectangle. Simulations have been made for this hypothetical earthquake at MDRS, VISK and PB stations indicated by solid red triangle simulated acceleration record at (b) MDRS, (c) VISK, and (d) PB stations, respectively. Pseudo acceleration response spectra obtained from simulated acceleration record at (e) MDRS, (f) VISK, and (g) PB stations

CONCLUSIONS

There are several techniques including semi empirical method, which can be used to simulate strong ground motion due to finite rupture source buried in a defined velocity medium. In this series the method of modified semi-empirical simulation of strong ground motion require less parameter for simulation, also it is very fast to calculate and is based on simple attenuation relations and modeling parameters which are easy to predict. In this work modified semi empirical technique is used to model great earthquake by using seismic moment and radiation pattern of the event instead of empirical attenuation relations for simulating strong ground motions of the Sumatra earthquake of 26th Dec, 2004 at various stations. The parameters like rupture velocity and starting point of rupture for this earthquake has been computed by iterative modeling and comparison of simulated and observed records at PSI station. Iterative modeling and comparison suggest that the rupture initiated at the western corner of rupture at a depth of 38 km and started propagating in all direction with rupture velocity 2.0 km/sec. The comparison of records from final model at MDRS and VISK stations confirms the efficacy of the approach and the suitability of final model for predicting strong ground motion due to this great earthquake. Using the parameters of final rupture model of the Sumatra earthquake, records due to a great hypothetical earthquake at northern segment of Andaman ridge has been simulated at PB station. The simulated record shows that peak ground acceleration of order 2663 gal can be observed at this station.

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